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(71) Applicant: CSO AKER MARITIME, INC. [US/US];
11700 Old Katy Road, Suite 150, Houston, TX 77079-1298
(US).

(72) Inventors: KARAYAKA, Metin; 8 Crest Gate, Houston, TX 77082 (US). STANTON, Paul, N.; 10106 Chevy Chase, Houston, TX 77042 (US).

(74) Agent: ARNOLD, Gordon, T.; Arnold & Associates, 2603 Augusta, Suite 800, Houston, TX 77057 (US).

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(54) Title: ENGINEERED MATERIAL BUOYANCY SYSTEM, DEVICE, AND METHOD

(57) Abstract: An engineered material buoyancy device, system and method is provided. Traditional buoyancy systems, useful, for example, on floating production platforms, are generally metal, and have limitations as to the amount of buoyancy, redundancy, and other features that the present invention addresses.

ENGINEERED MATERIAL BUOYANCY SYSTEM, DEVICE, AND METHOD

BACKGROUND

5 The present invention relates to the application of buoyancy to objects used in large vessel and platform operations.

Vast oil reservoirs have recently been discovered in very deep waters around the world, principally in the Gulf of Mexico, Brazil and West Africa. Water depths 10 for these discoveries range from 1500 to nearly 10,000 ft. Conventional offshore oil production methods using a fixed truss type platform are not suitable for these water depths. These platforms become dynamically active (flexible) in these water depths. Stiffening them to avoid excessive and damaging dynamic responses to wave forces is prohibitively expensive.

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Deep water oil and gas production has thus turned to new technologies based on floating production systems. These systems come in several forms, but all of them rely on buoyancy for support and some form of a mooring system for lateral restraint against the environmental forces of wind, waves and current.

20

These floating production systems (FPS) sometimes are used for drilling as well as production. They are also sometimes used for storing oil for offloading to a tanker. This is most common in Brazil and West Africa, but not in Gulf of Mexico as of yet. In the Gulf of Mexico, oil and gas are exported through pipelines to shore.

25

Drilling, production, and export of hydrocarbons all require some form of vertical conduit through the water column between the sea floor and the FPS. These conduits are usually in the form of pipes which are called "risers." Typical risers are either vertical (or nearly vertical) pipes held up at the surface by tensioning devices; 30 flexible pipes which are supported at the top and formed in a modified catenary shape to the sea bed; or steel pipe which is also supported at the top and configured in a catenary to the sea bed (Steel Catenary Risers – commonly known as SCRs).

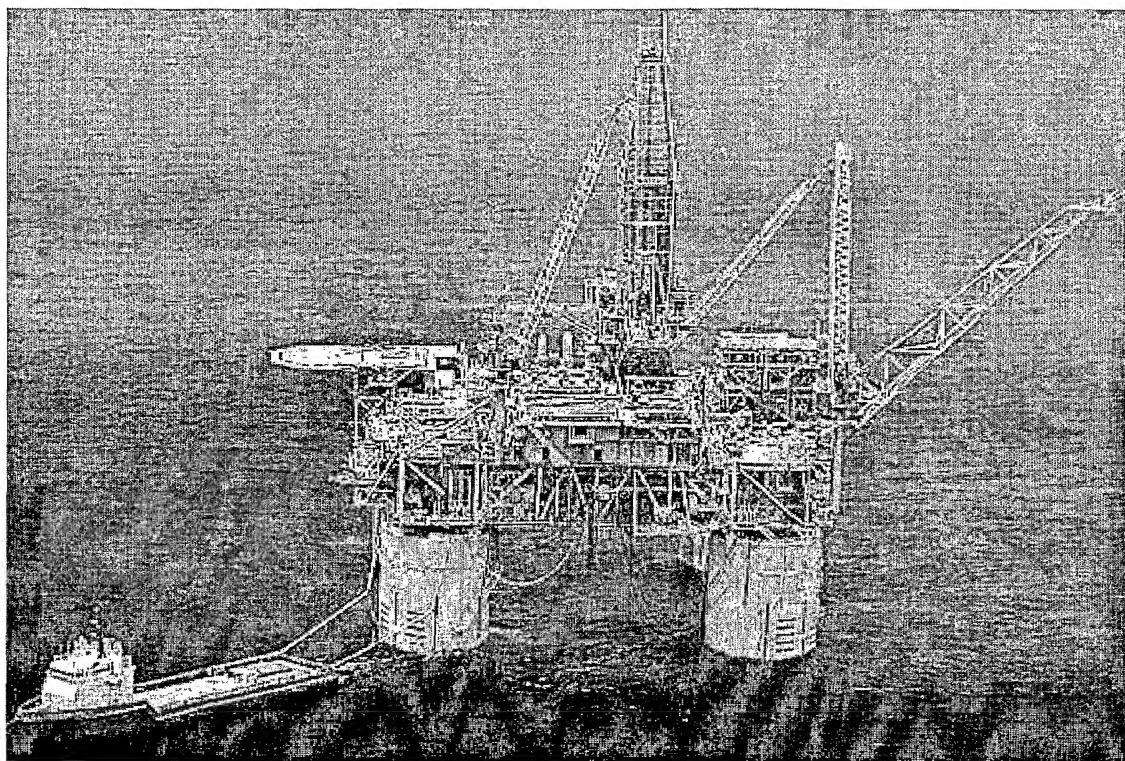
The flexible and SCR type risers may in most cases be directly attached to the floating vessel. Their catenary shapes allow them to comply with the motions of the FPS due to environmental forces. These motions can be as much as 10 – 20% of the 5 water depth horizontally, and 10s of ft vertically, depending on the type of vessel, mooring and location.

Top Tensioned risers (TTRs) typically need to have higher tensions than the flexible risers, and the vertical motions of the vessel need to be isolated from the 10 risers. TTRs have significant advantages for production over the other forms of risers, however, because they allow the wells to be drilled directly from the FPS, avoiding an expensive separate floating drilling rig. Also, wellhead control valves placed on board the FPS allow for the wells to be maintained from the FPS. Flexible 15 and SCR type production risers require the wellhead control valves to be placed on the seabed where access and maintenance is expensive. These surface wellhead and subsurface wellhead systems are commonly referred to as “Dry tree” and “Wet Tree” types of production systems, respectively.

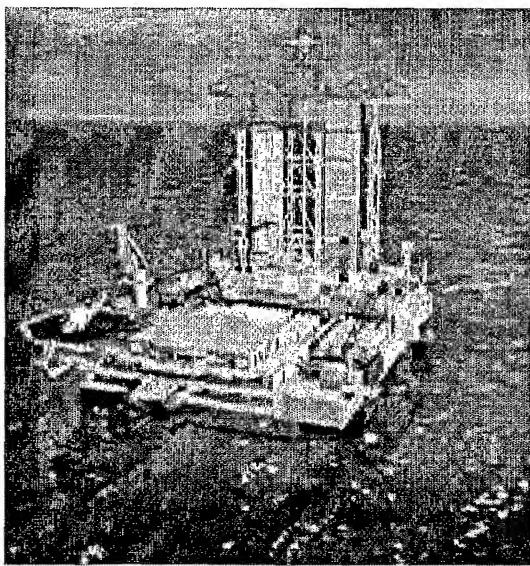
Drilling risers must be of the TTR type to allow for drill pipe rotation within 20 the riser.

Export risers may be of either type.

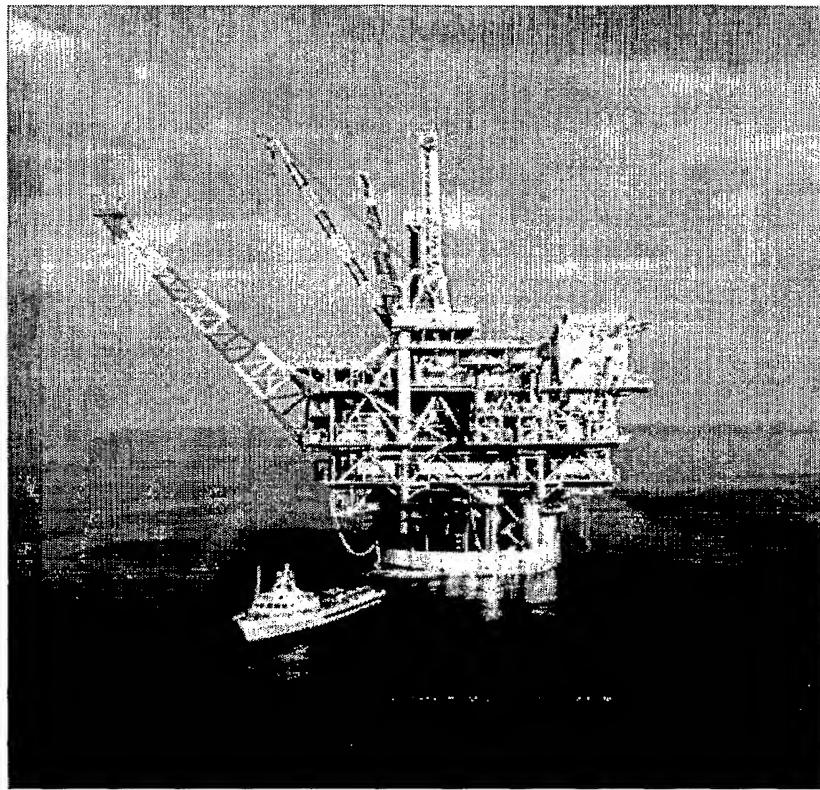
TTR tensioning systems are a technical challenge, especially in very deep 25 water where the required top tensions can be 1000 kips or more. Some types of FPS vessels, e.g. ship shaped hulls, have extreme motions which are too large for TTRs. These type of vessels are only suitable for flexible risers. Other, low heave (vertical motion), FPS designs are suitable for TTRs. This includes Tension Leg Platforms TLP), Semi-submersibles and Spars, all of which are in service today.



MARS Tension Leg Platform (from Shell Web Site)



5 SEDCO Express Semi submersible Drilling Rig (Transocean Sedco Web Site)



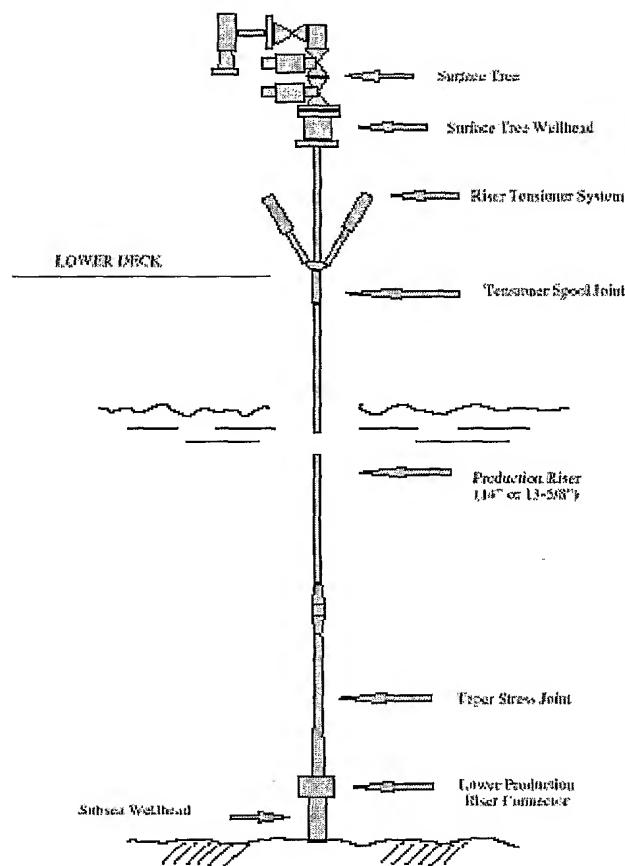
Chevron/Exxon "Genesis" Spar (Courtesy of Chevron)

5 Of these, only the TLP and Spar platforms use TTR production risers. Semi-submersibles use TTRs for drilling risers, but these must be disconnected in extreme weather. Production risers need to be designed to remain connected to the seabed in extreme events, typically the 100 year return period storm. Only very stable vessels are suitable for this.

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Early TTR designs employed on semi-submersibles and TLPs used active hydraulic tensioners to support the risers. As tensions and stroke requirements grow, these active tensioners become prohibitively expensive. They also require large deck area, and the loads have to be carried by the FPS structure.

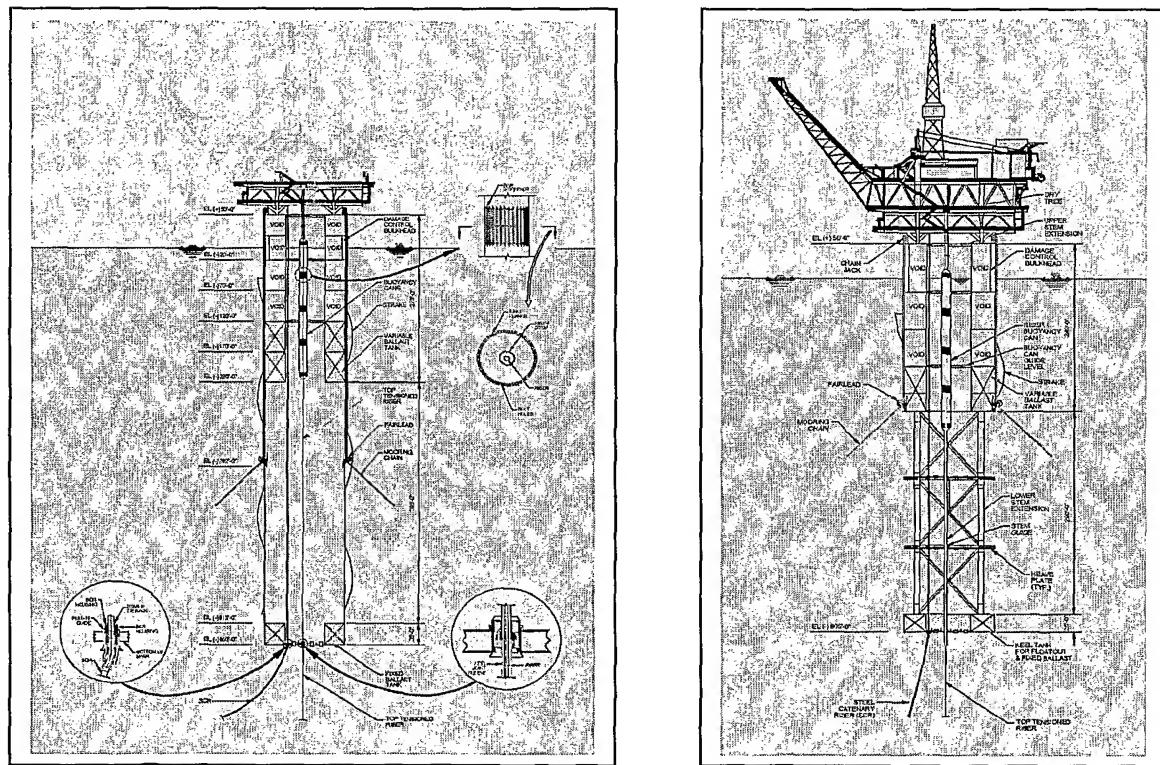
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TLP Riser System with Tensioners (Ursa Platform, from Offshore Technology Conference Paper 10758, 1999)

Spar type platforms recently used in the Gulf of Mexico use a passive means for tensioning the risers. These type platforms have a very deep draft with a central shaft, or centerwell, through which the risers pass. Buoyancy cans inside the centerwell provide the top tension for the risers. These cans are more reliable and less costly than active tensioners.

These figures show the arrangement of the risers in two types of spars: the Caisson Spar (cylindrical) and the “Truss” spar. There may be as many as 40 production risers passing through a single centerwell. The Buoyancy cans are typically cylindrical, and they are separated from each other by a rectangular grid structure referred to as the riser “guides”.

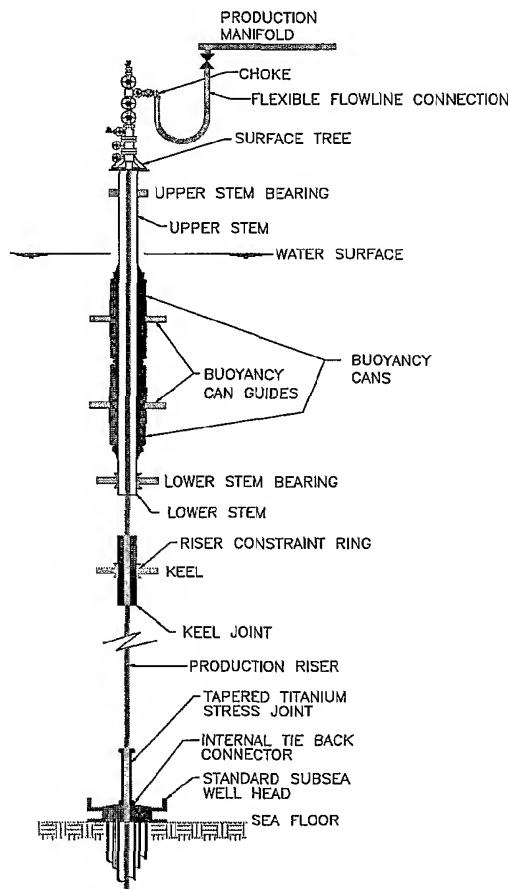


Caisson Spar and Truss Spar (Aker Maritime, Inc.)

These guides are attached to the hull. As the hull moves the risers are deflected horizontally with the guides. However, the risers are tied to the seafloor, hence as the vessel heaves the guides slide up and down relative to the risers (from the viewpoint of a person on the vessel it appears as if the risers are sliding in the guides).

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The following figure shows the arrangement for a single spar production riser.



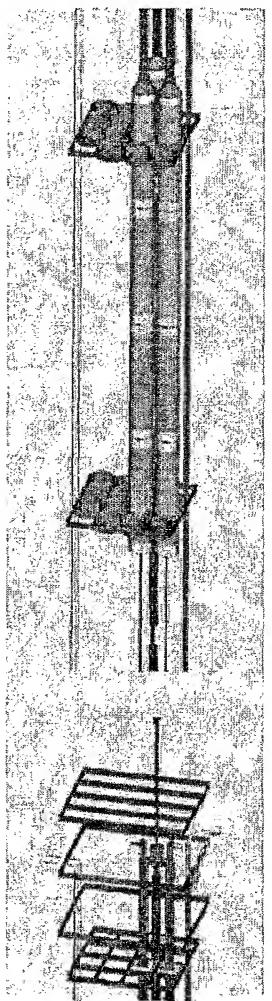
Spar Riser System (Aker Maritime, Inc.)

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A wellhead at the sea floor connects the well casing (below the sea floor) to the riser with a special Tieback Connector. The riser, typically 9 – 14" pipe, passes from the tieback connector through the bottom of the spar and into the centerwell. Inside the centerwell the riser passes through a stem pipe, or conduit, which goes through the center of the buoyancy cans. This stem extends above the buoyancy cans

themselves and supports the platform to which the riser and the surface wellhead is attached. The buoyancy cans need to provide enough buoyancy to support the required top tension in the risers, the weight of the cans and stem, and the weight of the surface wellhead.

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Buoyancy Cans and Guides in Spar Centerwell

Since the surface wellhead ("dry tree") move up and down relative to the vessel, flexible jumper lines connect the wellhead to a manifold which carries the 10 product to a processing facility to separate water, oil and gas from the well stream.

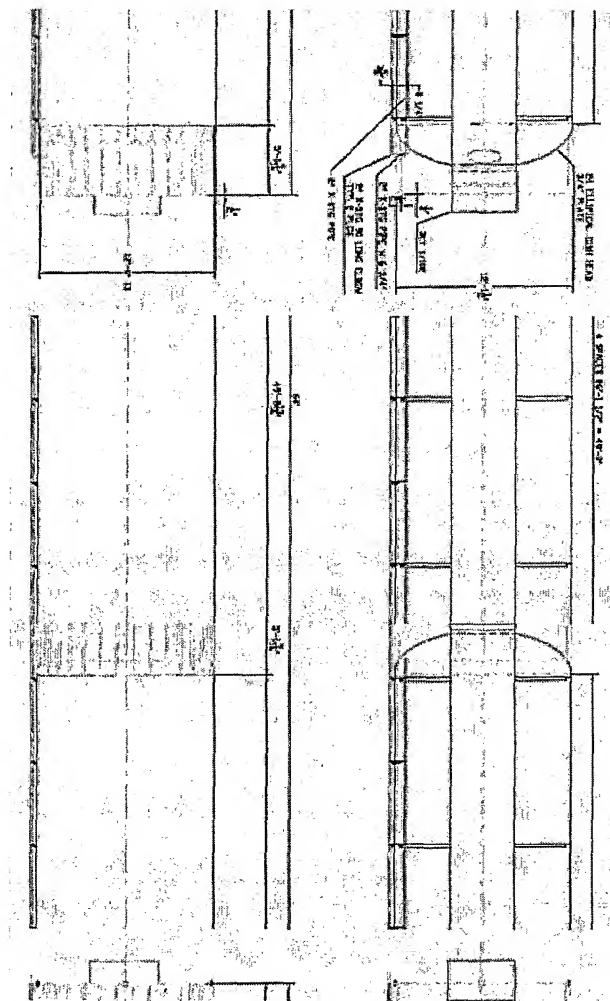
Spacing between risers is determined by the size of the buoyancy cans. This is an important variable in the design of the spar vessel, since the riser spacing

determines the centerwell size which in turn contributes to the size of the entire spar structure. This issue becomes increasingly more critical as production moves to deeper water because the amount of buoyancy required increases with water depth. The challenge is to achieve the buoyancy needed while keeping the length of the cans 5 within the confines of the centerwell, and the diameters to reasonable values.

The efficiency of the buoyancy cans is compromised by several factors:

10 Internal Stem

The internal stem is typically flooded and provides no buoyancy. Its size is dictated by the diameter of the seafloor tieback connector, which is deployed through the stem. These connectors can be up to 50" in diameter.



Typical Buoyancy Can Design Showing Outer Shell and Stem

Solutions to this loss of buoyancy include:

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1. adding compressed air to the annulus between the riser and the stem wall after the riser is installed, and
2. Making the buoyancy cans integral with the riser so they are deployed after the tieback connector is installed.

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Adding air to the annulus is efficient use of the stem volume, but the amount of buoyancy can be so large that if a leak occurs there could be damage to a riser. The

buoyancy tanks are usually subdivided so that leakage and flooding of any one, or even two, compartments will not cause damage.

Making the buoyancy cans integral with the risers has been used, but this 5 requires a relatively small can diameter for deployment with the surface rig, and the structural connections between the cans and the riser are difficult to design.

Circular Cans

10 The circular geometry of the cans leaves areas of the centerwell between cans flooded which could provide buoyancy if the cans were rectangular. Studies have shown, however, that rectangular or square cans have a greater structural weight and that the net buoyancy, i.e. the difference of the buoyancy and the can weight, is actually greater with the structurally more efficient circular shape.

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Weight of the Cans

20 The buoyancy cans are typically constructed out of steel and their weight can be a significant design issue. The first spar buoyancy cans were designed to withstand the full hydrostatic head of the sea, and their weight reflected the thicker walls necessary to meet this requirement. Subsequent designs were based on the cans being open to the sea at their lower end, with compressed air injected inside to 25 evacuate the water. These cans only have to be designed for the hydrostatic pressure corresponding to the can length, and this is an internal pressure requirement rather than the more onerous external pressure requirement.

Recently, studies have suggested that buoyancy cans could be fabricated from composite materials at costs which would be competitive with steel cans, and which would reduce the can weight significantly. These composite buoyancy modules 30 (CBMs) are the subject of a separate patent application entitled Composite Buoyancy Module, filed July 20, 2000 having a docket number T8803PROV.

The subject of this invention is a method for cost effective utilization of the space between the riser and the stem wall, and the flooded volumes between the circular buoyancy cans and the riser guides. The method uses specially designed composite modules, which are configured to straddle the riser pipe and steel buoyancy

5 modules in a way to use of the available flooded volume for additional buoyancy.

Other methods than those proposed here are feasible: in particular it is possible to shape and install closed cell syntactic foam modules in these areas to provide additional buoyancy. Syntactic foam modules are commonly used, especially on

10 drilling risers, to add buoyancy to the risers and reduce the top tension requirement. The primary advantages of the proposed invention over this more conventional means of adding buoyancy include:

1. Syntactic foam density is about 2-3 times as expensive as that derived from the
- 15 proposed composite cans (based on cost per unit of net buoyancy), and
2. Low density foam which is more cost effective in the shallow water applications such as the spar centerwell is subject to some water absorption and loss of buoyancy with time.

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While the above discussion focused on the problem of utilizing flooded volume for buoyancy on a spar type riser system, this invention has other similar applications. For example, as a replacement for syntactic foam on drilling risers, or

25 free standing production risers.

The arrangement of CBMs around a pipe can be such as to enhance the pipes hydrodynamic behavior in currents and waves. For example, arranging the CBMs in a spiral wrapped arrange would have an effect similar to helical strakes to mitigate

30 Vortex Induced Vibrations of pipes exposed to current or waves. Or, placing the CBMs on one side would have an effect similar to fairing the pipe to reduce drag.

SUMMARY OF THE INVENTION

The present invention relates to methods of designing, constructing, attaching and using buoyancy systems for water covered areas. Various objects of invention are 5 addressed in the above-mentioned problems. For example, according to one aspect of the invention, a buoyancy system for a structure having at least one component being substantially stationary with respect to the bottom of a water covered area is employed. This system comprises a set of buoyancy modules of engineered materials to apply an identified amount of buoyancy. The set of buoyancy modules are attached 10 to the structure at a set of buoyancy load transfer locations.

According to another aspect of the invention, a buoyant riser comprises a set of engineered-material buoyancy modules to the riser connected to the riser.

15 In a further example embodiment of the invention, a system of applying buoyancy to a member is adopted. This system comprises means for constraining a plurality of engineered material buoyancy members in a metal container, wherein said constraining is arranged to assert a buoyant force, and means for applying the buoyancy force of the metal container to the member.

20 Another aspect of the invention involves a system of applying buoyancy to a riser. That system comprises means for asserting a first portion of the buoyancy force required to lift the riser at a first buoyancy load location on the riser with a first buoyancy member, means for protecting the first buoyancy member from entry of 25 fluid, means for asserting a second portion of the buoyancy force required to lift the riser at a second buoyancy load location on the riser with a second buoyancy member, and means for protecting the second buoyancy member from entry of fluid.

30 Some embodiments of the invention utilize a system of applying buoyancy to a member. This system comprises means for resiliently constraining a mass having a density less than water and means for asserting, with the resiliently constrained mass,

at least a portion of the buoyancy force required to lift the member at a buoyancy load location on the member.

Still another embodiment of the invention applies a method of designing a
5 buoyancy system for a structure having at least one component being substantially stationary with respect to the bottom of a water covered area. Some of such methods comprise identifying the amount of buoyancy required by the buoyancy system, wherein an identified amount of buoyancy results, identifying a set of buoyancy modules of engineered material to apply the identified amount of buoyancy, and
10 identifying a location with respect to the structure for the set of buoyancy modules.

In accordance with another embodiment, the invention comprises a method of increasing the redundancy of a buoyancy in a stem pipe for a riser. In this embodiment, the method comprises applying a set of engineered-material buoyancy
15 modules to the riser, and inserting the riser with the set of engineered-material buoyancy modules attached to the stem pipe.

A still further example of the present invention comprises a method of applying buoyancy to a member. The method comprises constraining a plurality of
20 engineered material buoyancy members in a metal container, wherein said constraining is arranged to assert a buoyant force, and applying the buoyancy force of the metal container to the member.

In addition some embodiments of the invention comprise a method of applying buoyancy to a riser. A number of such methods comprise asserting a first portion of the buoyancy force required to lift the riser at a first buoyancy load location on the riser with a first buoyancy member, protecting the first buoyancy member from entry of fluid, asserting a second portion of the buoyancy force required to lift the riser at a second buoyancy load location on the riser with a second buoyancy member,
25 30 and protecting the second buoyancy member from entry of fluid.

Yet another embodiment of the invention comprises a method of applying buoyancy to a member. That method comprises resiliently constraining a mass having a density less than water and asserting, with the resiliently constrained mass, at least a portion of the buoyancy force required to lift the member at a buoyancy load 5 location on the member.

In accordance with various embodiments, the invention comprises an apparatus for providing buoyancy to a submerged riser attached at its lower end to a well head on the sea floor. This apparatus comprises a plurality of submerged 10 buoyancy modules associated with the riser for imparting an upward buoyancy force to the riser, wherein the buoyancy modules comprise lightweight material selected from a group consisting of glass fiber/polymeric resin, carbon fiber/polymeric resin, hybrid glass/carbon fiber polymeric resin, rubber reinforced with nylon fibers, and rubber reinforced with steel fibers.

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Further embodiments comprise an apparatus for providing buoyancy to a submerged riser attached at its lower end to a well head on the sea floor. That apparatus comprises a plurality of submerged buoyancy modules associated with the 20 riser for imparting an upward buoyancy force to the riser, wherein each buoyancy module is hollow and has an elongated shape with a longitudinal axis and is vertically oriented, the longitudinal axis of the buoyancy module being generally parallel to the longitudinal axis of the riser, some of the buoyancy modules being disposed at different vertical elevations along the riser in an arrangement so as to provide improved hydrodynamic performance to the riser, wherein each buoyancy module 25 comprises a layered exterior wall, wherein each layer of the wall has a specific function, and wherein the layers include one or more of hoop layers to resist internal and external pressure, axial layers to carry axial loads, polymeric liners to prevent fluid leakage through the wall, and selective reinforcing layers to provide damage tolerance at assembly contact locations and at buoyancy load transfer locations, and 30 straps for attaching the buoyancy modules to the riser, the straps passing around the outer circumference of the buoyancy modules.

These and many other embodiments and advantages of the present invention will be obvious to one of ordinary skill in the art upon review of the Detailed Description in conjunction with the following figures.

DESCRIPTION OF THE DRAWINGS

Figure 1 depicts a composite buoyancy module.

Figure 1a depicts detailed illustrations of layering of engineered materials.

Figure 2 depicts example cross-sections of shapes of buoyancy devices that can be used to improve hydrodynamic properties.

Figure 3 depicts example mass containment systems.

Figure 3a depicts an example air containment system wherein the mass is held by a manufactured material having an open bottom with a substantially constant pressure supplied by a vessel.

Figure 3b depicts an example air containment system wherein the mass is held by a manufactured material having an open bottom with a substantially constant pressure supplied by an attached object.

Figure 3c depicts an example pressured and enclosed mass containment system.

Figure 3d depicts an example enclosed mass containment system.

Figure 4 depicts aspects of the invention comprising various buoyancy module configurations with improved hydrodynamic properties.

Figure 5 depicts example buoyancy load transfer systems.

Figure 6 depicts aspects of the invention comprising various buoyancy module configurations and shapes with associated water current patterns.

Figure 7 depicts aspects of the invention comprising various riser applications.

Figure 8 depicts various center stem, riser, and buoyancy can applications.

Figure 9a depicts an example assembly of five CBM's on a riser joint.

Figure 9b-d depict various details of the example assembly of five CBM's on a riser joint.

DETAILED DESCRIPTION OF EXAMPLE EMBODIMENTS OF THE INVENTION

According to one example embodiment of the invention, airtight composite buoyancy modules (CBMs) provide buoyancy to attached objects submerged underwater. Different sizes and shapes of CBMs are attached in various embodiments to, for example, production risers, drilling riser, catenary risers, air cans, and stem pipe.

In the example embodiments illustrated, buoyancy is provided by trapping air inside structures of engineered materials (for example: glass fiber/ polymeric resin, carbon fiber/polymeric resin, hybrid glass/carbon fiber polymeric resin, engineered rubber reinforced with nylon or steel fibers).

Referring now to Figure 1, a CBM 10 is seen, having a wall 12 of layers 12a – 12n (seen in Fig. 1a) of engineered materials. Various layers of the layers 12a – 12n have differing functions. For example, some of the layers 12a – 12n comprise hoop layers (substantially horizontal orientation of fiber) to resist internal and external pressure. Other of layers 12a – 12n comprise axial layers (substantially vertical fibers) to carry axial loads. Still other layers comprise internal polymeric liners to prevent air leakage to outside and water leakage to inside, outside polymeric liners to prevent water leakage to inside and air leakage to outside, layers to provide damage tolerance (e.g. thick, but un-reinforced layers and/or layers of materials differing from those of the adjacent layers, or layers having differing microstructures from other layers – honeycomb layers, etc.), and selective reinforcing layers 14 (Fig. 1) at the contact/assembly locations. Further, in accordance with a more specific embodiment of the invention, fiber optic 26 is manufactured in or between layers 12a – 12n for use in monitoring the state of the CBM 10. Any variety of combinations of layers are used in alternative embodiments of the invention, there being no particular layer combination that must be used in all embodiments of the invention. Further, there is no particular single layer type that must be used in every embodiment of the invention.

Referring again to Figure 1, selective reinforcement at the buoyancy load transfer locations 16 is provided in some embodiments. In one such embodiment, seen in Figure 1b, reinforcing member 18 (for example, a metal or other load-bearing material, in a more specific example, corrosion-resistant alloy ("CRA")) is provided to support wall 10. Optional selective reinforcement 20 is seen for further load transfer aid.

Referring again to Figure 1, an example penetration 22 is seen, which is provided in some embodiments for air pressurization. A further penetration 26 is seen for passing of fiber optic 26. It will be noted that the location of penetrations is dependant upon the use of the penetration, and, while shown both on the side and at the end of CBM 10, penetrations at the end of CBM 10 are preferable for many applications. Other uses of such penetrations include water purging and other functions that will occur to those of skill in the art. Multiple penetrations are contemplated in various embodiments; however, in some embodiments single or no penetrations are used. Also seen in Figure 1 is a bulkhead 24, used on some embodiments to increase the collapse resistance of the CBM 10. Bulkhead 24 is also used on some embodiments to add redundancy.

20

In many embodiments of the invention wall 12 of CBM 10 is designed to leak before collapse or burst. In still further embodiments, the functional status of the CBM 10 is detected by monitoring the pressurizing system and/or air flow rate into the system. In still further embodiments, wall 12 is designed such that, in the case of burst, the CBM is not shattered into large pieces. In an even further embodiment, when the CBMs fail due to leakage of water inside the chamber, the structural integrity of the CBM is maintained such that it can carry axial loads without providing buoyancy.

30 Referring now to Figures 2a – 2d, the cross-sectional area of CBM 10 is, in alternative embodiments, cylindrical, hexagonal, or other non-symmetric forms. Other forms will occur to those of ordinary skill without departing from the spirit of

the invention. Also, length of the CBM 10 is variable (for example, between 1 ft to 50 ft), depending on the manufacturing process or the attachment requirements.

Referring now to Figures 3a – 3d, in still further embodiments, air, or any other material that is less dense than water, is trapped inside the CBM 10. In one non-limiting example, the CBM 10 is open to water 27 at the bottom 10a. The amount of water inside the CBM is varied by supplying air from a supply line 30 connected to a supply (not shown) located at the surface facilities (not shown). Alternatively, as seen in Figure 3b, air is plumbed through supply 34 from the object 32 (e.g., a steel air can, neighboring CBM, etc.) to which the CBM 10 is attached. In embodiments providing for pressure supply, the buoyancy of the system is adjusted, both on location and during installation. Thus, for example, during installation the buoyancy is adjusted in some embodiments so that the CBM 10 does not provide upward thrust.

Referring now to the embodiment of Figure 3c, the CBM 10 is designed for internal pressure loads. In one example use embodiment of the invention, CBM 10 is pressurized through penetration 39 on the surface. Then, when CBM 10 is submerged, hydrostatic pressure works against the internal pressure and balances the load, simplifying the design of wall 12. In such cases, less material/layers (or weaker material/layers) is needed than in embodiments in which there is a high external pressure differential. In further embodiments, the internal pressure is used to test the CBM for leaks.

Referring now to Figure 3d, a more simple embodiment is seen in which internal pressure in CBM 10 is below that of the pressure outside CBM 10 (for example, one atmosphere), and CBM 10 is constructed without a penetration and with sufficient strength to take the full hydrostatic pressure loads.

In still a further embodiment, CBM 10, from what ever drawing mentioned above, comprises a rubber wall 12. In a more specific embodiment, wall 12 comprises a reinforced rubber walls allow for deflection, reducing the potential for damage of CBM 10.

Referring now to Figures 4a – 4d, various system embodiments of the invention are seen, in which various numbers, sizes, and/or shapes of CBMs 10 are attached to a member 40 to which added buoyancy is desired. The CBM 10 increase 5 the effective hydrodynamic diameter of attached objects. By arranging the CBM assembly to different shapes the drag and lift coefficients of the system can be optimized.

Referring now to Figures 6a- 6c, embodiments are seen in which 10 hydrodynamic performance is adjusted. In the embodiment of Figure 6a, for example, in which CBM 10a is a size different from CBM size 10b, the current 60 is disrupted from the pattern it would normally take around the shape of the member 40 on which additional buoyancy is desired. A variety of patterns is available through selection of size and orientation of the CBMs. In Figure 3b, and example embodiment is seen in 15 which CBMs 10a – 10d are attached to member 40 such that current 60 passes both around CBMs 10a – 10d and between CBMs 10a – 10d and member 40. Again, various patterns are available through selection of the size, number, and orientation of the CBMs. Likewise, shape of the CBMs affects the hydrodynamic performance. As seen in Figure 6c, CBMs 10 a – 10e are of a non-circular cross-sectional shape, in this 20 case a triangle. Again, variation in number, relative size and orientation also are combined in even further alternative embodiments. Likewise, other shapes are also within the scope of the invention.

Referring now to Figure 9a a more specific example of an assembly of 5 25 CBMs 10a – 10e on a riser joint 90 is seen, suitable for installation in (as seen in Fig. 9b) a 51" stem pipe 92. Referring again to Figure 9a, the CBMs 10a – 10e are attached to riser joint 90 with retaining rings 94. A thrust plate assembly 91, with gussets 91a – 91e, transfer the buoyancy forces from the CBMs 10a – 10c to riser joint 90. Stopper assembly 93, prevents CBMs 10a – 10e from shifting axially down 30 riser joint 90. Alternative embodiments of load transfer assembly 91 and stopper 93 will occur to those of ordinary skill in the art.

Referring now to Figures 9b – 9d, retaining ring 94 holds CBMs 10a – 10e concentrically around riser 90 with spacers 98 to centralize the CBMs 10a – 10e, avoid damage to the CBMs. Acceptable materials for spacers 98 include: rubber, HDPE, teflon, extruded polymers, and other materials that will occur to those of skill in the art. Bumpers 96 prevent the CBMs from being damaged during installation. Acceptable materials for bumpers 96 include: rubber HDPE, teflon, extruded polymers, and other materials that will occur to those of skill in the art. Retaining ring 94 comprises semi-rings 94a and 94b, attached by flange, nut, and bolt assemblies 96a and 96b. Other attachments of semi-rings 94a and 94b will occur to those of skill in the art (e.g. welds, rivets, clamps, locking tabs, etc.). Further other ring assemblies will occur to those of skill in the art without departing from the spirit of the invention. In some specific embodiments, the material of ring 94 comprises material such as, for example: CRA alloys, Kevlar straps, and other tension bearing members and/or fabrics.

15 Load Transfer

Referring now to Figures 5a – 5b, various example embodiments are seen of CBMs 10 attached to members 40 to provide buoyancy to member 40. In Figure 5a, for example, a single, long CBM 10 is attached with thrust plate 91 and rings 94. To add redundancy and reduce the danger of the loss of any single CBM causing insufficient buoyancy, Figure 5b shows the same amount of buoyancy for the member 40 by using multiple CBMs. In Figure 5b, a load transfer member 99 transfers the buoyancy forces between CBMs 10a – 10c to thrust plate 91. The use of modular CBMs in an overall CBM system with load transfer members 99 results in the replacement of the single CBM of the example of Figure 5a. Thus, if CBM 10b leaks and provides no buoyancy, the structure of CBM 10b is sufficient to transfer the buoyancy load of CBM 10c to CBM 10a and to thrust plate 91. According to an event further embodiment of the invention, the CBM assembly of Figure 5b is assembled in modular form, wherein a damaged part is removed and replaced, again obtaining advantages over the embodiment of Figure 5a or the earlier air cans.

In still a further embodiment, seen in Figure 5c, a single CBM or even a CBM assembly such as what is seen in Figure 5b, is attached to member 40 with clamps 100, and the buoyancy load is transferred to member 40 through the friction interaction between the CBM assembly, the clamps, and the surface of the member.

5

According to various embodiments of the invention, various manufacturing processes are used to make the CBMs and CBM assemblies discussed above. For example, one such method comprises filament winding of CBMs (most suitable for cylindrical uniform cross-section elements). Another acceptable method comprises 10 resin transfer molding (suitable for non-symmetric cross-section elements). Hand lay-up walls on “pultruded” composite elements is yet a further acceptable manufacturing embodiment. Other manufacturing processes will occur to those of skill in the art.

According to an even further embodiment of the invention, systems are 15 configured with a large number of CBMs such that each CBM will supply only a small fraction of total required buoyancy. By dividing the buoyancy elements in to smaller units overall system redundancy is increased. The CBMs are designed to be inspectable and easily repairable/disposable. Figure 7 illustrates a more specific embodiment in which CBMs are applied to top tension risers. The CBMs are placed 20 at different locations along the riser, rather than using a few large buoyancy elements.

In still a further embodiment, Figure 8a is an application of CBMs for a spar riser system. A large portion of the buoyancy required by the system is provided by the steel air can, divided into multiple chambers 110a – 110 c. Without CBMs, the 25 interior of stem 112 is not normally counted upon for buoyancy, because it is too large and uncompartmentalized. A leak in the stem, anywhere, results in a loss of all of the buoyancy. Attachment of the CBMs 10 to the riser 40 as shown allows the stem interior to be used, reliably, for buoyancy. The loss of one or even many of the CBMs 10 in such an embodiment does not mean the loss of all of the buoyancy of the stem. 30 Likewise, the loss of air pressure within the stem itself does not affect the buoyancy provided by the CBMs. Therefore, the Figure 8a buoyancy system is designed for failure of several chambers. Likewise, the compartments 110a – 110c of the air can

110 are large, and a small leak can cause the loss of buoyancy of all of the compartment. Therefore, in still a further embodiment, seen in Figure 8b, multiple CBMs are applied to the interior of air can compartments 110a – 110c, again to add redundancy.

What is claimed is:

- 1 1. A buoyancy system for a structure having at least one component being substantially stationary with respect to the bottom of a water covered area, the system comprising a set of buoyancy modules of engineered materials to apply an identified amount of buoyancy; the set of buoyancy modules being attached to the structure at a set of buoyancy load transfer locations.
- 1 2. The buoyancy system as in claim 1 wherein said set of buoyancy modules comprise layers of the engineered materials.
- 1 3. The buoyancy system as in claim 2 wherein said engineered materials comprise a substantially horizontally reinforced layer.
- 1 4. The buoyancy system as in claim 3 wherein said engineered materials comprise a substantially vertically reinforced layer.
- 1 5. The buoyancy system as in claim 2 wherein said engineered materials comprise a substantially vertically reinforced layer.
- 1 6. The buoyancy system as in claim 2 wherein said engineered materials comprise a leak prevention layer.
- 1 7. The buoyancy system as in claim 6 wherein said leak prevention layer comprises an inside leak prevention layer.
- 1 8. The buoyancy system as in claim 6 wherein said leak prevention layer comprises an outside leak prevention layer.
- 1 9. The buoyancy system as in claim 2 wherein the layers of the engineered materials comprise layers which will leak upon failure.

1 10. The buoyancy system as in claim 1 wherein said set of buoyancy modules
2 comprises cylindrical shapes.

1 11. The buoyancy system as in claim 1 wherein said set of buoyancy modules
2 comprises triangular shapes.

1 12. The buoyancy system as in claim 1 wherein said set of buoyancy modules
2 comprises hexagonal shapes.

1 13. The buoyancy system as in claim 1 wherein said set of buoyancy modules
2 comprises saddle shapes.

1 14. The buoyancy system as in claim 1 wherein said set of buoyancy modules
2 comprises truncated, pie-slice shapes.

1 15. The buoyancy system as in claim 1 wherein said set of buoyancy modules
2 comprises octagonal shapes.

1 16. A buoyant riser comprising a set of engineered-material buoyancy modules
2 connected to a riser having negative buoyancy.

1 17. A system of applying buoyancy to a member, the system comprising:
2 means for constraining a plurality of engineered material buoyancy members in a metal
3 container, wherein said constraining is arranged to assert a buoyant force, and means
4 for applying the buoyancy force of the metal container to the member.

1 18. The system as in claim 17 wherein said means for constraining is substantially
2 air-tight.

1 19. The system as in claim 17 wherein said engineered material buoyancy members
2 comprise a substantially horizontally reinforced layer.

- 1 20. The system as in claim 19 wherein said engineered material buoyancy members
- 2 comprise a substantially vertically reinforced layer.

- 1 21. The system as in claim 17 wherein said engineered material buoyancy members
- 2 comprise a substantially vertically reinforced layer.

- 1 22. The system as in claim 17 wherein said engineered material buoyancy members
- 2 comprise a leak prevention layer.

- 1 23. The system as in claim 22 wherein the leak prevention layer comprises an inside
- 2 leak prevention layer.

- 1 24. The system as in claim 22 wherein the leak prevention layer comprises an
- 2 outside leak prevention layer.

- 1 25. The system as in claim 17 wherein said engineered material buoyancy members
- 2 comprise layers that leak upon failure.

- 1 26. The system as in claim 17 wherein said plurality of engineering material
- 2 buoyancy members comprises cylindrical shapes.

- 1 27. The system as in claim 17 wherein said plurality of engineering material
- 2 buoyancy members comprises triangular shapes.

- 1 28. The system as in claim 17 wherein said plurality of engineering material
- 2 buoyancy members comprises hexagonal shapes.

- 1 29. The system as in claim 17 wherein said plurality of engineering material
- 2 buoyancy members comprises saddle shapes.

- 1 30. The system as in claim 17 wherein said plurality of engineering material
- 2 buoyancy members comprises truncated, pie-slice shapes.

1 31. The system as in claim 17 wherein said plurality of engineering material
2 buoyancy members comprises octagonal shapes.

1 32. A system of applying buoyancy to a riser, the system comprising:
2 means for asserting a first portion of the buoyancy force required to lift the riser
3 at a first buoyancy load location on the riser with a first buoyancy member;
4 means for protecting the first buoyancy member from entry of fluid;
5 means for asserting a second portion of the buoyancy force required to lift the
6 riser at a second buoyancy load location on the riser with a second buoyancy member;
7 and
8 means for protecting the second buoyancy member from entry of fluid.

1 33. The system as in claim 32 further comprising means for protecting the first
2 buoyancy member from passage of gas into the water.

1 34. The system as in claim 32 wherein said first buoyancy member comprises a
2 constrained mass having a density less than water and wherein the system further
3 comprises means for preventing the constrained mass from contacting the water.

1 35. A system of applying buoyancy to a member, the system comprising:
2 means for resiliently constraining a mass having a density less than water and
3 means for asserting, with the resiliently constrained mass, at least a portion of
4 the buoyancy force required to lift the member at a buoyancy load location on the
5 member.

1 36. The system as in claim 35 further comprising means for protecting the
2 constrained mass from entry of fluid.

1 37. The system as in claim 35 wherein said means for constraining comprises a
2 material having a compressional load bearing capability.

1 38. The system in claim 37 further comprising means for providing a leak-failure
2 mode to said means for constraining.

1 39. The system as in claim 38 wherein said leak-failure mode substantially
2 maintains the compressional load bearing capability of the material.

1 40. The system as in claim 35 further comprising means for providing a leak-failure
2 mode to said constraining.

1 41. The system as in claim 35 wherein said means for constraining comprises a
2 corrosion-resistant wall.

1 42. The system as in claim 35 further comprising means for monitoring the state of
2 the means for constraining.

1 43. The system as in claim 42 wherein said means for monitoring comprises a fiber
2 optic.

1 44. A method of designing a buoyancy system for a structure having at least one
2 component being substantially stationary with respect to the bottom of a water covered
3 area, the method comprising:

4 identifying the amount of buoyancy required by the buoyancy system, wherein
5 an identified amount of buoyancy results;

6 identifying a set of buoyancy modules of engineered material to apply the
7 identified amount of buoyancy; and

8 identifying a location with respect to the structure for the set of buoyancy
9 modules.

1 45. The method according to claim 44 further comprising identifying buoyancy
2 module failure sensing types.

1 46. The method according to claim 45 wherein the identifying buoyancy module
2 failure sensing types comprises designing an interior-exterior pressure difference
3 sensor.

1 47. The method according to claim 45 wherein the identifying buoyancy module
2 failure sensing types comprises designing an interior pressure sensor.

1 48. The method according to claim 45 wherein the identifying buoyancy module
2 failure sensing types comprises designing an interior temperature sensor.

1 49. The method according to claim 45 wherein the identifying buoyancy module
2 failure sensing types comprises designing a buoyancy force transfer monitor.

1 50. The method according to claim 45 wherein the identifying buoyancy module
2 failure sensing types comprises designing an interior moisture sensor.

1 51. The method as in claim 44 wherein said identifying the set of buoyancy
2 modules comprises identifying the functions of the buoyancy modules.

1 52. The method as in claim 44 wherein said identifying the set of buoyancy
2 modules comprises identifying layers of the engineered material.

1 53. The method as in claim 52 wherein the identifying layers of engineered
2 materials comprises identifying a substantially horizontally reinforced layer.

1 54. The method as in claim 53 wherein the identifying layers of engineered
2 materials comprises identifying a substantially vertically reinforced layer.

1 55. The method as in claim 52 wherein the identifying layers of engineered
2 materials comprises identifying a substantially vertically reinforced layer.

1 56. The method as in claim 52 wherein the identifying layers of engineered
2 materials comprises identifying a leak prevention layer.

1 57. The method as in claim 56 wherein the identifying a leak prevention layer
2 comprises identifying an inside leak prevention layer.

1 58. The method as in claim 57 wherein the identifying a leak prevention layer
2 comprises identifying an outside leak prevention layer.

1 59. The method as in claim 56 wherein the identifying a leak prevention layer
2 comprises identifying an outside leak prevention layer.

1 60. The method according to claim 44 wherein said identifying the set of buoyancy
2 modules comprises designing redundancy into the at least one buoyancy module.

1 61. The method according to claim 60 wherein the designing redundancy into the at
2 least one buoyancy module comprises selecting a structure to transfer a buoyant force
3 from the upper, outer shell of a first buoyancy module to the lower, outer shell of a
4 second buoyancy module.

1 62. The method according to claim 60 wherein the designing redundancy into the at
2 least one buoyancy module comprises dividing the interior of the at least one buoyancy
3 module into at least two compartments.

1 63. The method according to claim 60 wherein the designing redundancy into the at
2 least one buoyancy module comprises selecting the at least one buoyancy module
3 wherein the interior of the at least one buoyancy module is divided.

1 64. The method as in claim 52 wherein the identifying layers of the engineered
2 material comprises identifying layers that leak upon failure.

1 65 The method according to claim 44 wherein said identifying a location with
2 respect to the structure comprises reinforcing the at least one buoyancy module to
3 facilitate buoyancy force distribution to the member.

1 66. The method as in claim 44 wherein said identifying a location with respect to
2 the structure for the set of buoyancy modules comprises identifying loading locations
3 on the structure for the buoyancy force to be applied.

1 67. The method as in claim 44 wherein said identifying a location with respect to
2 the structure for the set of buoyancy modules comprises identifying shapes of buoyancy
3 modules for current deflection.

1 68. The method as in claim 67 wherein said identifying a location with respect to
2 the structure for the set of buoyancy modules comprises identifying numbers of
3 buoyancy modules for current deflection.

1 69. A method of increasing the redundancy of a buoyancy in a stem pipe for a riser,
2 the method comprising:
3 applying a set of engineered-material buoyancy modules to the riser, and
4 inserting the riser, with the set of engineered-material buoyancy modules
5 attached, into the stem pipe.

1 70. A method of applying buoyancy to a member, the method comprising:
2 constraining a plurality of engineered material buoyancy members in a metal
3 container, wherein said constraining is arranged to assert a buoyant force, and
4 applying the buoyancy force of the metal container to the member.

1 71. The method as in claim 70 wherein said constraining is substantially air-tight.

1 72. A method of applying buoyancy to a riser, the method comprising:
2 asserting a first portion of the buoyancy force required to lift the riser at a first
3 buoyancy load location on the riser with a first buoyancy member;

4 protecting the first buoyancy member from entry of fluid;
5 asserting a second portion of the buoyancy force required to lift the riser at a
6 second buoyancy load location on the riser with a second buoyancy member; and
7 protecting the second buoyancy member from entry of fluid.

1 73. The method as in claim 72 further comprising protecting the first buoyancy
2 member from passage of gas into the water.

1 74. The method as in claim 72 wherein said first buoyancy member comprises a
2 constrained mass having a density less than water and wherein the method further
3 comprises preventing the constrained mass from contacting the water.

1 75. A method of applying buoyancy to a member, the method comprising:
2 resiliently constraining a mass having a density less than water and
3 asserting, with the resiliently constrained mass, at least a portion of the
4 buoyancy force required to lift the member at a buoyancy load location on the member.

1 76. The method as in claim 75 further comprising protecting the constrained mass
2 from entry of fluid.

1 77. The method as in claim 75 wherein said constraining comprises using a material
2 having a compressional load bearing capability.

1 78. The method as in claim 77 further comprising providing a leak-failure mode to
2 said constraining.

1 79. The method as in claim 78 wherein said leak-failure mode substantially
2 maintains the compressional load bearing capability of the material.

1 80. The method as in claim 75 further comprising providing a leak-failure mode to
2 said constraining.

1 81. The method as in claim 75 wherein said constraining comprises corrosion-
2 resistant constraining.

1 82. The method as in claim 75 further comprising monitoring the state of the
2 constraining.

1 83. Apparatus for providing buoyancy to a submerged riser attached at its lower end
2 to a well head on the sea floor; which comprises:

3 a plurality of submerged buoyancy modules associated with the riser for
4 imparting an upward buoyancy force to the riser, wherein the buoyancy modules
5 comprise lightweight material selected from a group consisting of glass fiber/polymeric
6 resin, carbon fiber/polymeric resin, hybrid glass/carbon fiber polymeric resin, rubber
7 reinforced with nylon fibers, and rubber reinforced with steel fibers.

1 84. The apparatus of claim 83, wherein each buoyancy module has an elongated
2 shape with a longitudinal axis and is vertically oriented, the longitudinal axis of the
3 buoyancy module being generally parallel to the longitudinal axis of the riser, and
4 wherein the cross sectional shape of the buoyancy module on a plane perpendicular to
5 the longitudinal axis is a shape selected from the group consisting of a circle, a triangle,
6 a square, a polygon, a hexagon, a truncated pie slice, and a saddle.

1 85. The apparatus of claim 84, further including a horizontally oriented bulkhead
2 disposed within the buoyancy module for providing structural rigidity to the buoyancy
3 module.

1 86. The apparatus of claim 84, wherein the buoyancy module is generally
2 cylindrically shaped with dome shaped upper and lower ends.

1 87. The apparatus of claim 86, further including a thrust plate disposed at the upper
2 end of the buoyancy module and attached to the riser for supporting the buoyancy
3 module from the riser and for transmitting buoyancy force from the buoyancy module
4 to the riser.

1 88. The apparatus of claim 87, wherein the thrust plate includes a conical receptacle
2 on its bottom for receiving the dome shaped upper end of the buoyancy member.

1 89. The apparatus of claim 88, wherein the conical receptacle on the thrust plate has
2 an elastomeric interior lining for protecting the upper end of the buoyancy member.

1 90. The apparatus of claim 83, wherein each buoyancy module is hollow, the
2 hollow interior being filled with air, and further including means in the wall of the
3 buoyancy module for admitting air into the buoyancy module and for releasing air from
4 the buoyancy module.

1 91. The apparatus of claim 83, wherein each buoyancy module is hollow, the
2 hollow interior being filled with low density material.

1 92. The apparatus of claim 91, wherein the low density material is closed cell
2 syntactic foam.

1 93. The apparatus of claim 91, wherein the low density material is flowable
2 microspheres.

1 94. The apparatus of claim 91, wherein the low density material is a gas other than
2 air.

1 95. The apparatus of claim 83, wherein each buoyancy module is attached to the
2 riser by at least one strap associated with the riser and passing around the outer
3 circumference of the buoyancy module.

1 96. The apparatus of claim 83, further including at least one submerged air can
2 associated with the riser, wherein the buoyancy modules are attached to the exterior
3 surface of the air can.

1 97. The apparatus of claim 83, further including at least one submerged air can
2 associated with the riser, the air can having a hollow interior, wherein the buoyancy
3 modules are disposed within the hollow interior of the air can for providing buoyant
4 redundancy to the air can in the event of fluid leakage into the air can.

1 98. The apparatus of claim 83, wherein some of the submerged buoyancy modules
2 are disposed at the same vertical elevation on the riser, but are distributed uniformly
3 around the outer circumference of the riser in a geometrical arrangement so as to
4 provide improved hydrodynamic performance to the riser.

1 99. The apparatus of claim 83, wherein the submerged buoyancy modules are
2 disposed at different vertical elevations along the riser in an arrangement so as to
3 provide improved hydrodynamic performance to the riser.

1 100. The apparatus of claim 99, wherein the submerged buoyancy modules are
2 disposed in a stacked arrangement along a common vertical axis, and wherein the ends
3 of adjacent pairs of modules are connected together by skirts conforming to the shapes
4 of the ends of the modules.

1 101. The apparatus of claim 100, wherein the skirts comprise elastomeric material.

1 102. The apparatus of claim 83, wherein selected portions of the exterior surface of
2 each buoyancy module are structurally reinforced for protecting the module from
3 crushing forces where the module transfers buoyancy force to the riser and where the
4 buoyancy module is attached to the riser.

1 103. The apparatus of claim 83, wherein each buoyancy module comprises a layered
2 exterior wall, wherein each layer of the wall has a specific function, and wherein the
3 layers include one or more of substantially horizontal layers to resist internal and
4 external pressure, substantially vertical layers to carry axial loads, polymeric liners to
5 prevent fluid leakage through the wall, and selective reinforcing layers to provide
6 damage tolerance at assembly contact locations and at buoyancy load transfer locations.

1 104. The apparatus of claim 83, wherein each buoyancy module is hollow and is
2 open on its lower end for permitting sea water to rise within the buoyancy module for
3 compressing entrapped air in the upper portion of the buoyancy module.

1 105. Apparatus for providing buoyancy to a submerged riser attached at its lower end
2 to a well head on the sea floor; which comprises:

3 a plurality of submerged buoyancy modules associated with the riser for
4 imparting an upward buoyancy force to the riser, wherein each buoyancy module is
5 hollow and has an elongated shape with a longitudinal axis and is vertically oriented,
6 the longitudinal axis of the buoyancy module being generally parallel to the
7 longitudinal axis of the riser, some of the buoyancy modules being disposed at different
8 vertical elevations along the riser in an arrangement so as to provide improved
9 hydrodynamic performance to the riser, each buoyancy module providing a small
10 fraction of the total buoyancy from all the modules for purposes of redundancy;

11 wherein each buoyancy module comprises a layered exterior wall, wherein each
12 layer of the wall has a specific function, and wherein the layers include one or more of
13 hoop layers to resist internal and external pressure, axial layers to carry axial loads,
14 polymeric liners to prevent fluid leakage through the wall, and selective reinforcing
15 layers to provide damage tolerance at assembly contact locations and at buoyancy load
16 transfer locations; and

17 straps for attaching the buoyancy modules to the riser, the straps passing around
18 the outer circumference of the buoyancy modules.

1 106. The apparatus of claim 105, wherein the buoyancy modules comprise
2 lightweight material selected from a group consisting of glass fiber/polymeric resin,
3 carbon fiber/polymeric resin, hybrid glass/carbon fiber polymeric resin, rubber
4 reinforced with nylon fibers, and rubber reinforced with steel fibers.

1 107. The apparatus of claim 105, further including a horizontally oriented bulkhead
2 disposed within the buoyancy module for providing structural rigidity to the buoyancy
3 module.

1 108. The apparatus of claim 105, wherein the cross sectional shape of the buoyancy
2 module on a plane perpendicular to the longitudinal axis is a shape selected from the
3 group consisting of a circle, a triangle, a square, a polygon, a hexagon, a truncated pie
4 slice, and a saddle.

1 109. The apparatus of claim 108, wherein the buoyancy module is generally
2 cylindrically shaped with dome shaped upper and lower ends.

1 110. The apparatus of claim 108, further including a thrust plate disposed at the
2 upper end of the buoyancy module and attached to the riser for supporting the
3 buoyancy module from the riser and for transmitting buoyancy force from the
4 buoyancy module to the riser, wherein the thrust plate includes a receptacle on its
5 bottom for receiving the upper end of the buoyancy member.

1 111. The apparatus of claim 105, wherein the hollow interior of each buoyancy
2 module is filled with air, and further including means in the wall of the buoyancy
3 module for admitting air into the buoyancy module and for releasing air from the
4 buoyancy module.

1 112. The apparatus of claim 105, wherein the hollow interior of each buoyancy
2 module is filled with low density material.

1 113. The apparatus of claim 105, further including at least one submerged air can
2 associated with the riser, wherein the buoyancy modules impart buoyancy force to the
3 air can.

1 114. The apparatus of claim 105, wherein some of the submerged buoyancy modules
2 are disposed at the same vertical elevation on the riser, but are distributed uniformly
3 around the outer circumference of the riser in a geometrical arrangement so as to
4 provide improved hydrodynamic performance to the riser.

1 115. The apparatus of claim 105, wherein some of the submerged buoyancy modules
2 are disposed in a stacked arrangement along a common vertical axis, and wherein the
3 ends of adjacent pairs of modules are connected together by skirts conforming to the
4 shapes of the ends of the modules.

1 116. The apparatus of claim 105, wherein each buoyancy module is open on its lower
2 end for permitting seawater to rise within the buoyancy module for compressing
3 entrapped air in the upper portion of the buoyancy module.

1 / 8

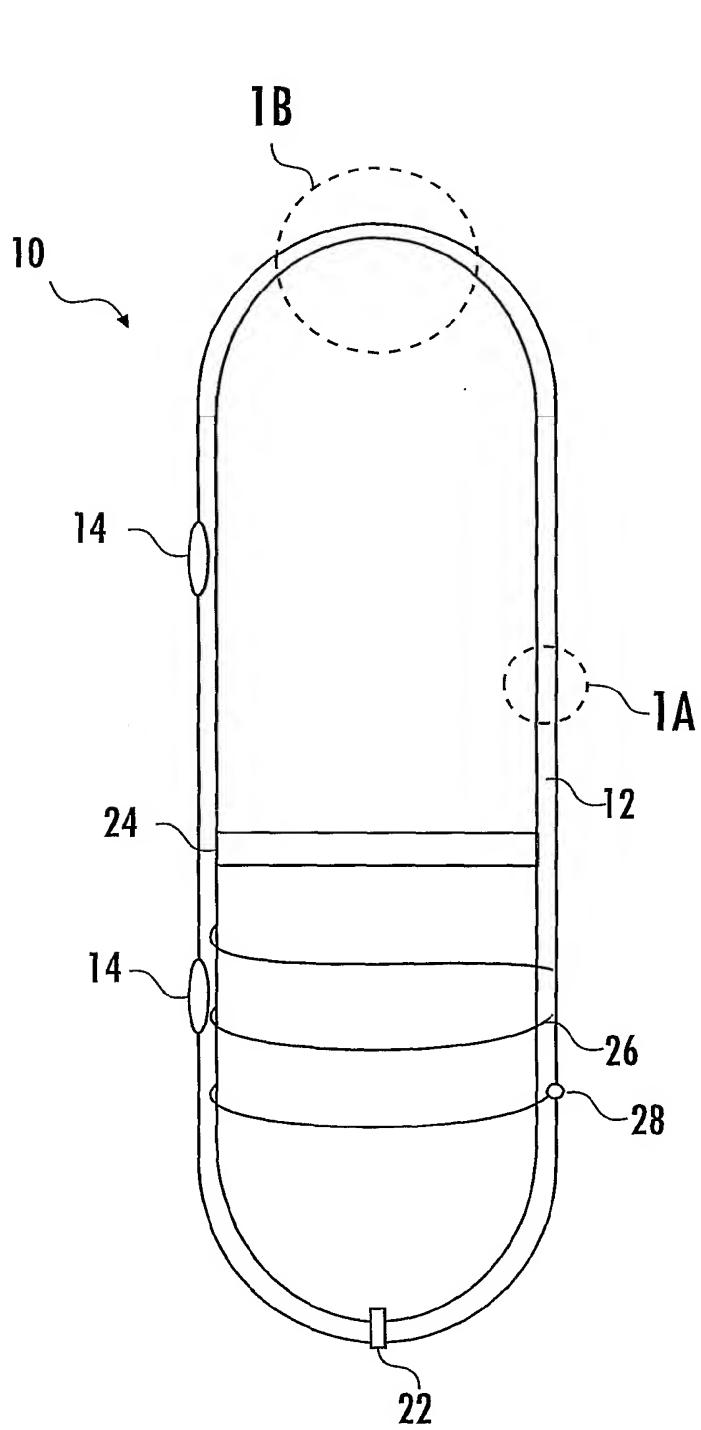
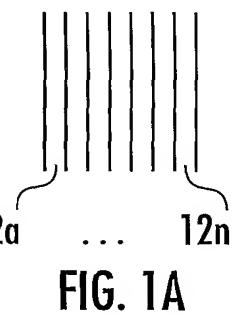
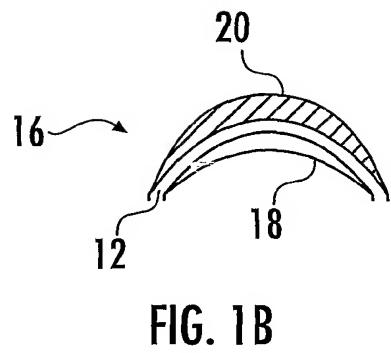


FIG. 1



2 / 8

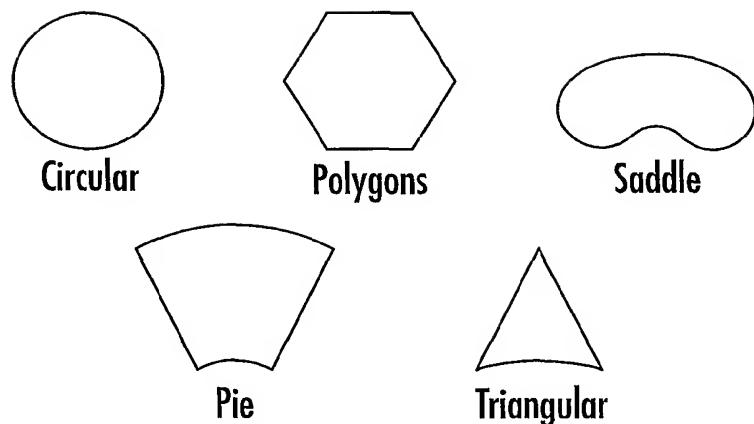
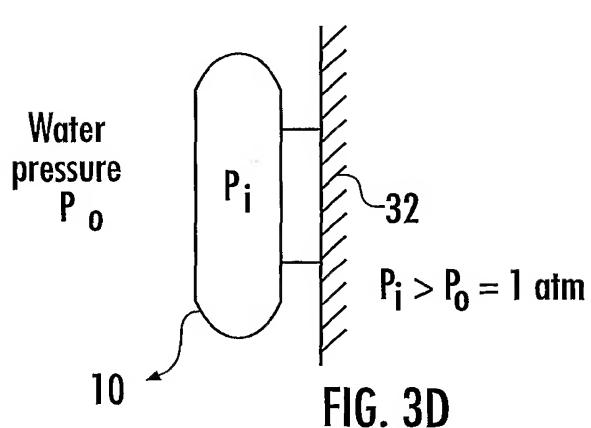
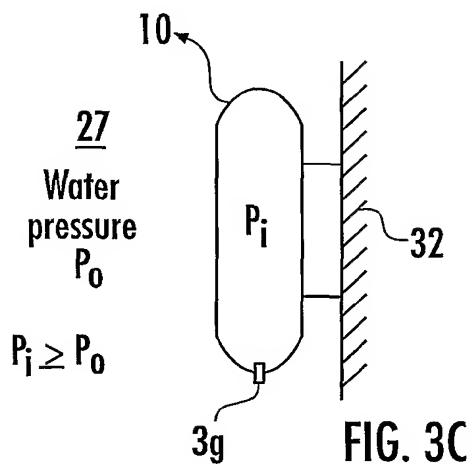
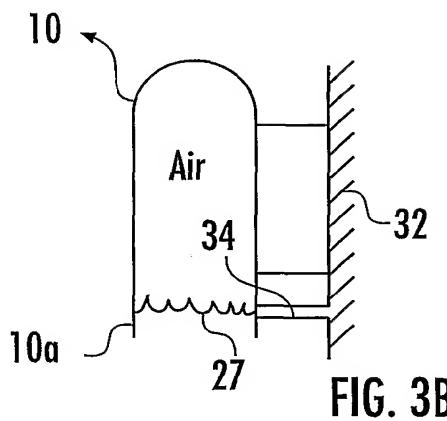
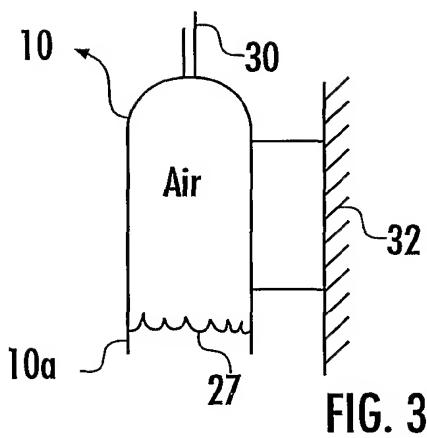


FIG. 2



3 / 8

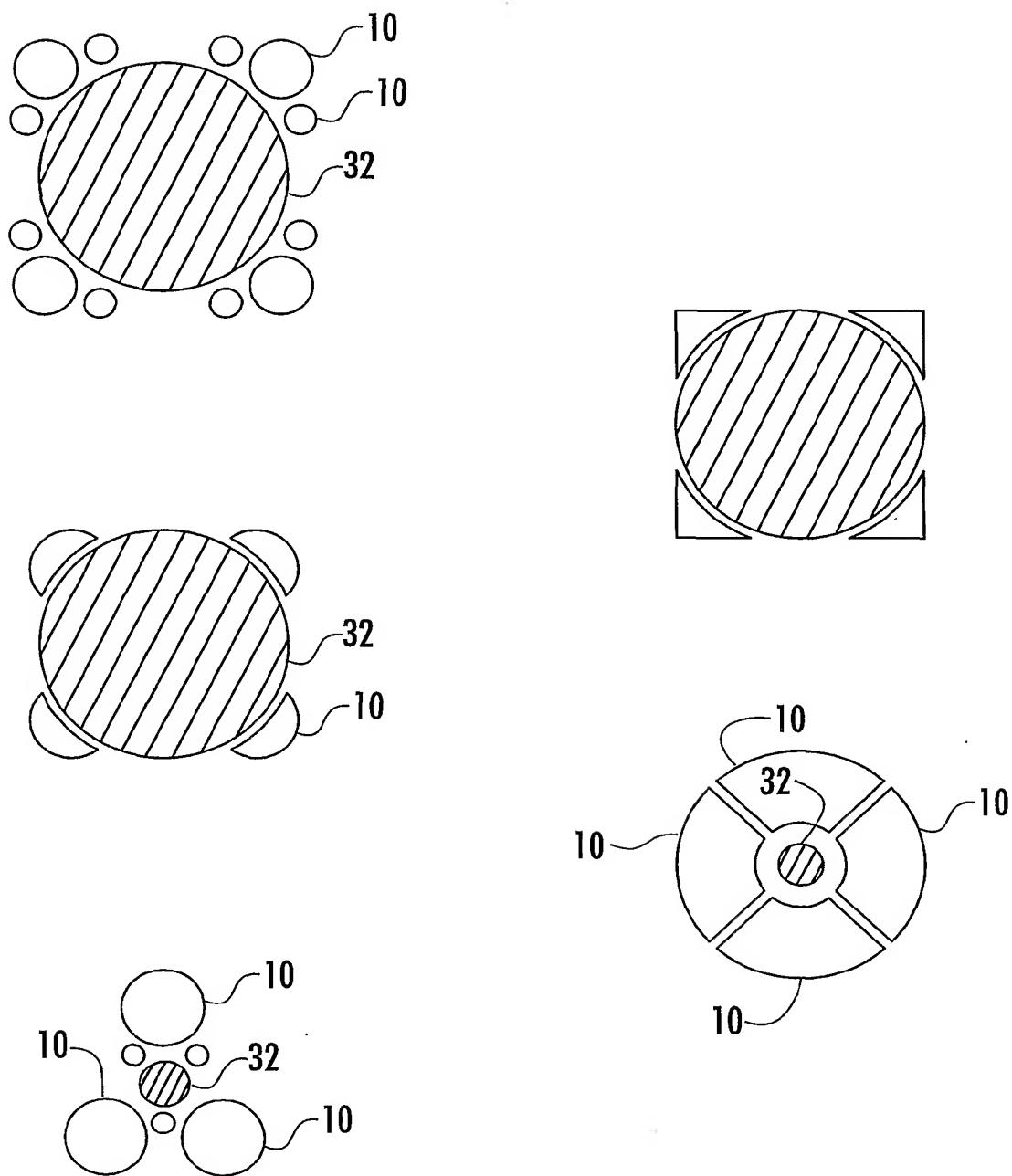


FIG. 4

4 / 8

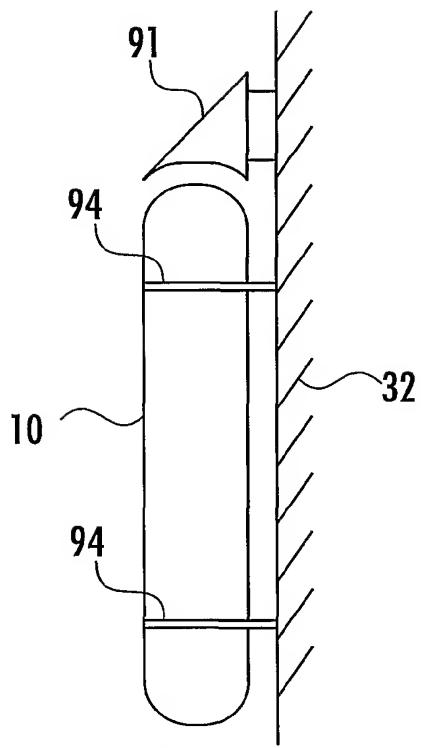


FIG. 5A

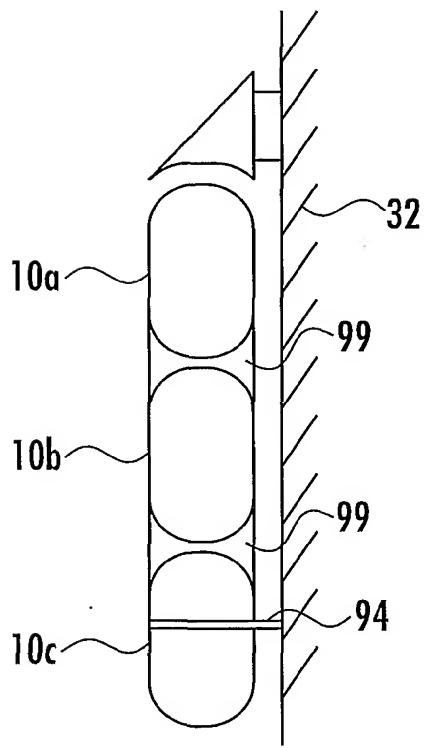


FIG. 5B

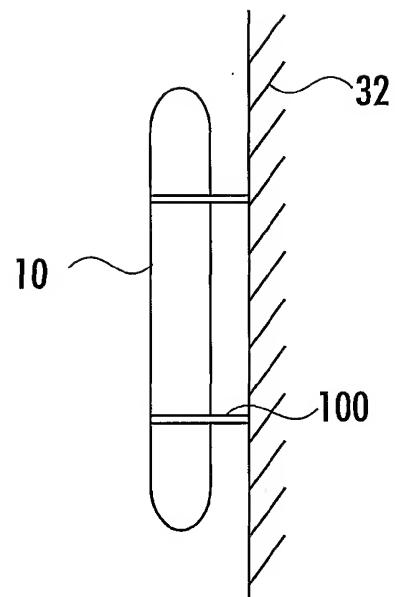


FIG. 5C

5 / 8

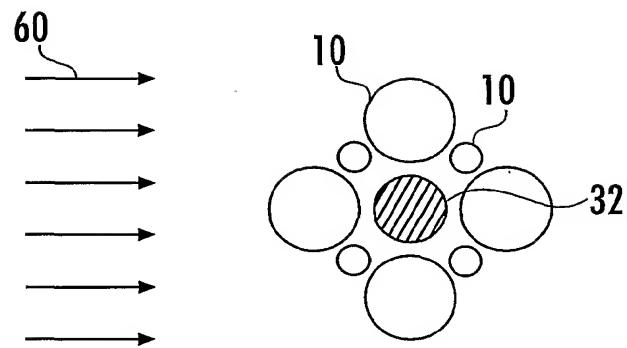


FIG. 6A

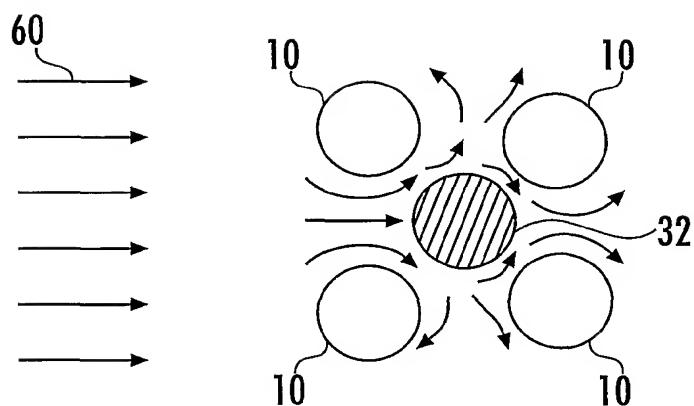


FIG. 6B

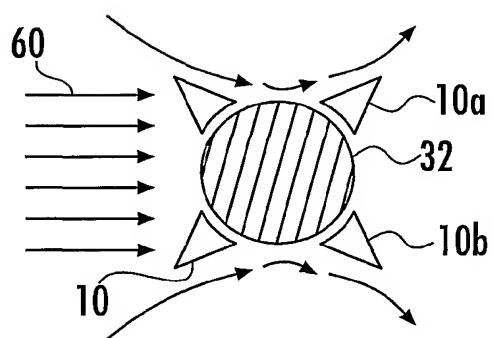
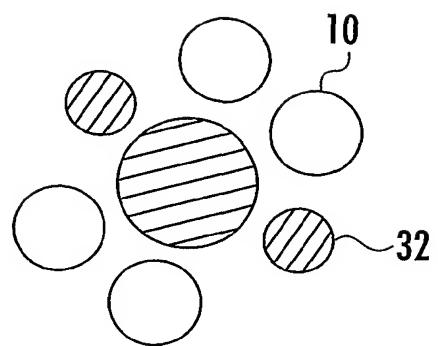
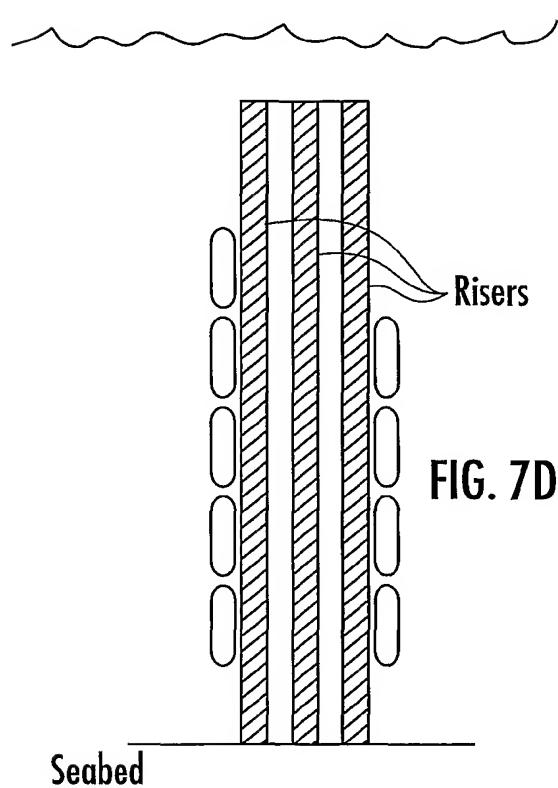
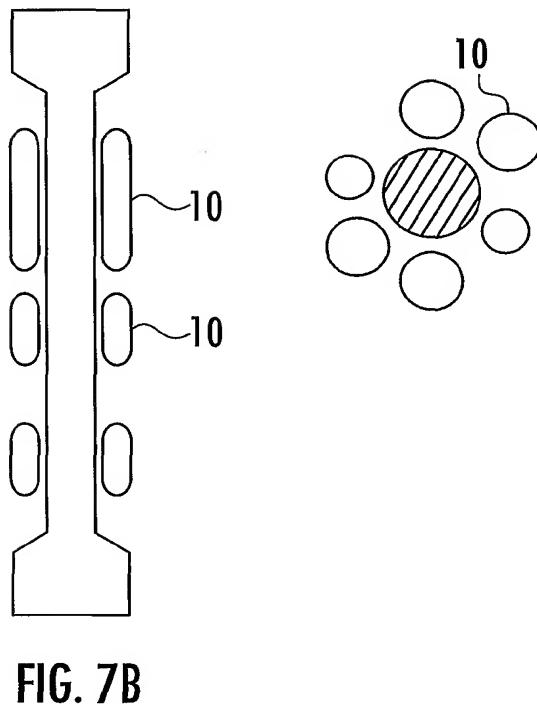
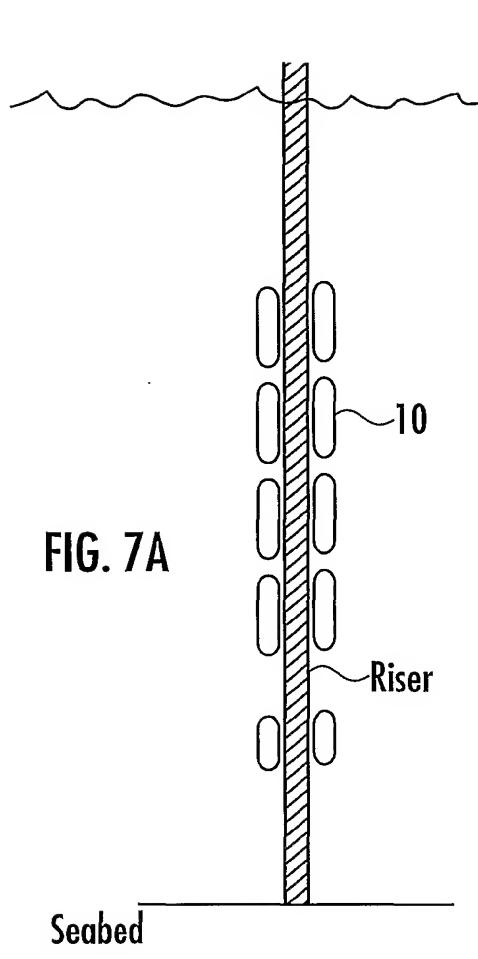


FIG. 6C



7 / 8

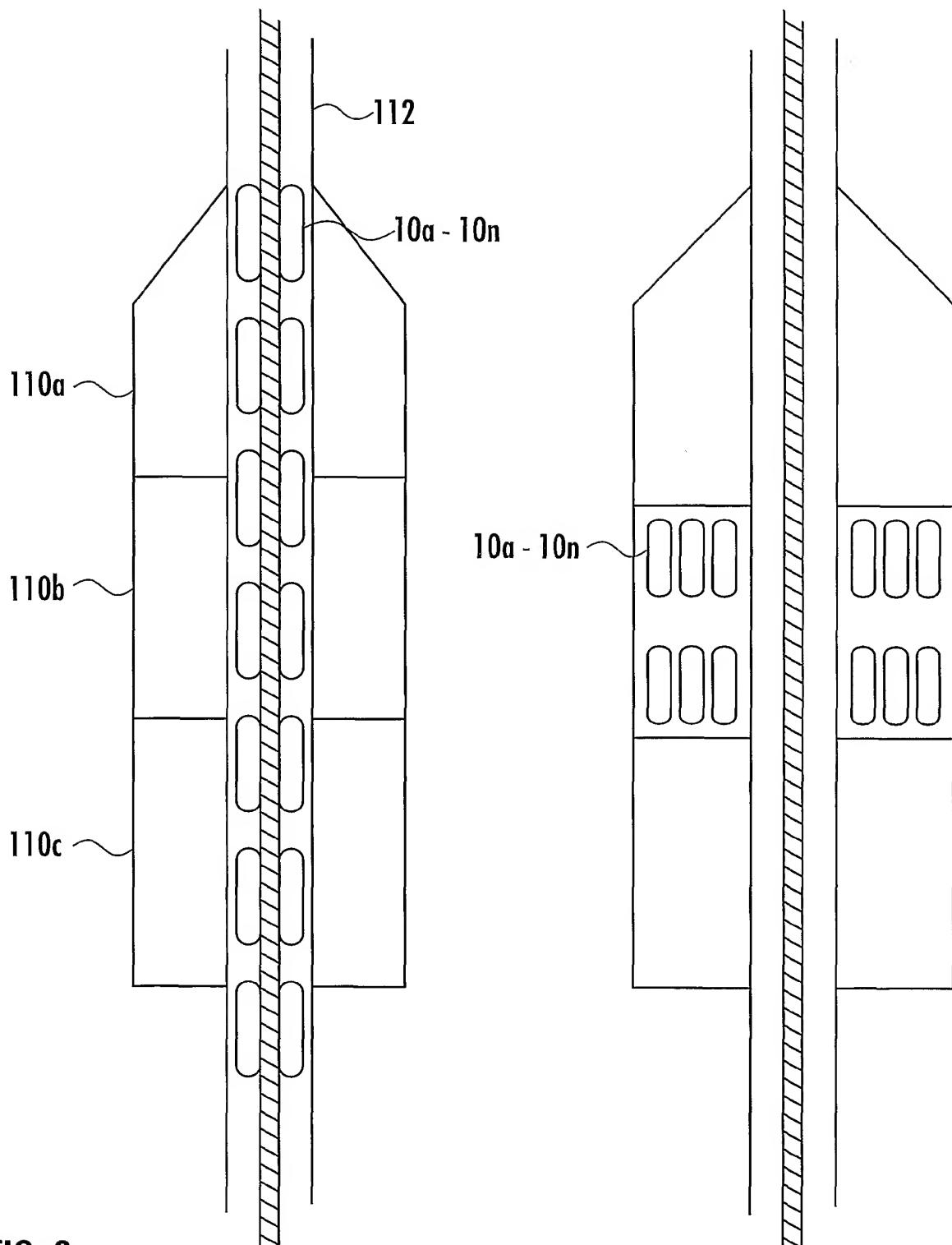


FIG. 8

8 / 8

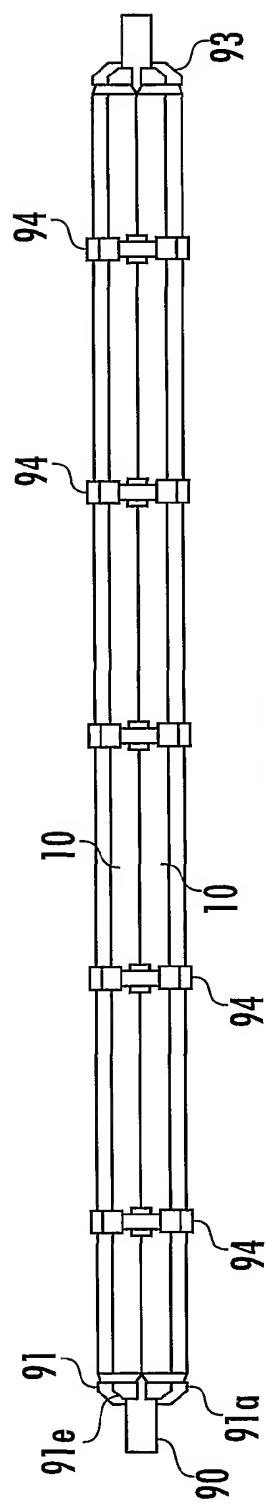


FIG. 9A

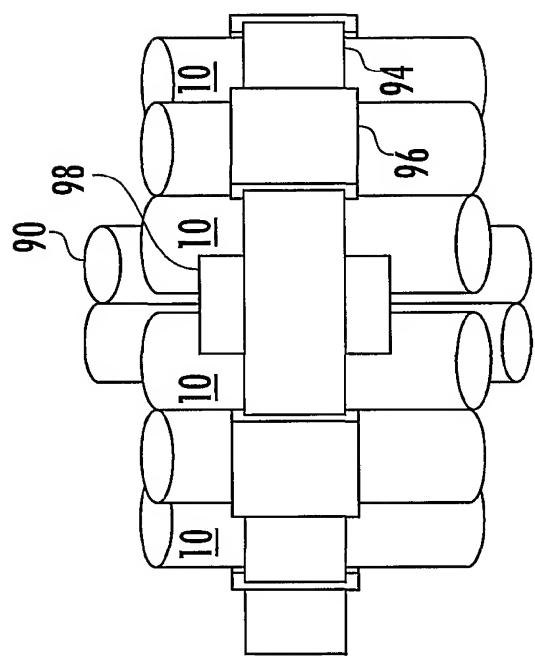


FIG. 9C

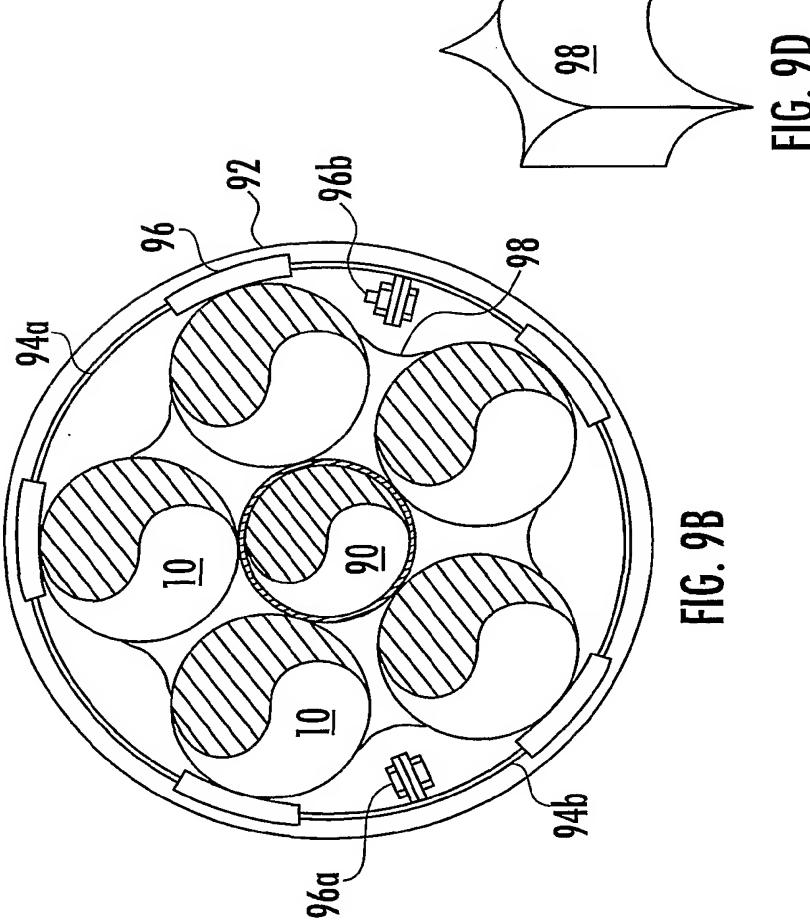


FIG. 9B